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EVALUATION AND DEVELOPMENT OF FLUID ARMOR SYSTEMS

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CULVER CITY, CALIFORNIA

TECHNICAL REPORT AFML-TR-68-362

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LOUIS E. GATES, JR.

FOREWORD

This report was prepared by the Hughes Aircraft Company, Materials Technology Department, Research and Development Division, Aerospace Group, Culver City, California 90230, under USAF Contract No. F33615-68-C1246, Project 7381 "Materials Application," Task 738108 "Materials and Processes for Limited War Support." The work was administered by the Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio 45433, with Mr. R. E. Wittman (MAAE), Project Engineer.

This report covers work performed from 1 January 1968 to 30 September 1968. The report was submitted October 1968.

Mr. L. E. Gates, Jr., was the principal investigator. Other contributors to the program were Mr. B. G. Kimmel, assisting in composite design; Mr. J. A. Stahmann, dilatant fluids characterization; Mr. C. J. Bahun, statistical analyses; and Mr. J. V. DeLuca, composite fabrication and impact testing. Advice and assistance of Mr. R. K. Kirkpatrick and Mr. D. N. Tarr in impact test setup are gratefully acknowledged.

Many of the items compared in this report were commercial items that were not developed or manufactured to meet Government specifications, to withstand the tests to which they were subjected, or to operate as applied during this study. Any failure to meet the objectives of this study is no reflection on any of the commercial items discussed herein or on any manufacturer.

This technical report has been reviewed and is approved.

Albert Olevitch

Albert Olevitch, Chief
Materials Engineering Branch
Materials Support Division

ABSTRACT

Results are presented on a 9-month evaluation program on resistance to penetration of a highly dilatant fluid by 30-caliber ball and AP bullets. Military ammunition of both types was fired point blank into test cells containing the fluid packaged according to these general concepts: (1) flexible, (2) semi-flexible, (3) conformable rigid, and (4) rigid. The principal objective was to find a fully-flexible system that could use the unusual self-healing capability of the material. Degrees of effectiveness of the various packaging systems for confining the fluid are described in this report. Packaging materials that were tested included commercial fiberglass, high tensile strength plastic, and aluminum honeycomb materials. Cell reinforcements studied included reticulated foam and various grades of screen wire mesh. In an effort to improve shear and short-range tensile strengths of the dilatant fluid, asbestos, metal, and ceramic fiber additives were evaluated. From these tests, Hughes concluded that the dilatant fluid is not competitive with conventional ceramic faced armor on weight or volume bases. But there are indications that the material would be effective if it were tightly constrained in a specially designed, high-strength core material. The fluid is shown to improve coupling between layers of flexible high strength fabrics used for protection of personnel against ballistic fragments.

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SECTION 1

INTRODUCTION

A semi-fluid ceramic material discovered at Hughes Aircraft Company and designated Fluid Armor was shown to be capable of stopping high velocity soft lead bullets within a short distance. It appeared to be effective in absorbing and distributing impact forces over a wide area. This program was initiated to evaluate the effectiveness of Fluid Armor in stopping conventional military ball and armor piercing bullets. Since the material has very low shear and tensile strengths, it was necessary to devise packaging schemes in attempts to cause the material to impose frictional and compressive forces sufficient to stop a bullet. Fluid Armor was attractive from a weight standpoint, having a density about 28 percent of the density of steel. The constituents comprising the material are cheap, readily available, and non-strategic. Armor fabrication costs were expected to be low.

SECTION II

OBJECTIVES

This program consisted of an engineering investigation of Fluid Armor, a highly dilatant fluid, as a substitute for presently used armor in several specific southeast Asia operations applications. The objectives were determinations of capabilities of compositions already formulated, in combination with other materials, to reduce cost and weight of presently employed armor materials.

Studies conducted on dilatant fluids were directed toward determining liquid-solids ratio to produce maximum dilatancy and to observe the effects on impact resistance of adding short staple fibers to the dilatant mixture.

Various cellular packaging schemes were designed to distribute and absorb bullet impact energy transmitted by Fluid Armor. The objective was to determine the best packaging schemes for further study and application to specific armor problems.

SECTION III

EXPERIMENTAL WORK

1. DESCRIPTION OF DILATANT FLUID

"Fluid Armor" is a thick viscous fluid that pours slowly like heavy molasses. When the material is subjected to sudden impact, it becomes hard and resists penetration — a characteristic of dilatant material. Soft lead bullets fired into it are broken up and stopped within a short distance.

Dilatancy (as commonly accepted among ceramists) is a rather rarely encountered rheologic property of certain fluid suspensions of fine particles. Examples of dilatant behavior are observed in quicksand and in trodding upon semi-firm wet sand at the ocean shore. Sand particles are conchoidally fractured into roughly spherical shapes. Such particles in fluid suspension at high packing densities will exhibit this behavior under any pressure sufficient to cause point contact to become established between particles through the fluid film. The fluid moves a short distance to adjacent regions of lower pressure, and the particles become locked together as a solid material in the high pressure region. Under low forces, such as gentle pressure or gravity, the fluid film is not penetrated and particles lubricated by the fluid film are free to flow to new positions. The bulk density of a dilatant composition is very close to maximum theoretical packing density of uniform diameter spheres of the disperse (particulate) phase. Closely packed spheres have been shown to exhibit highest dilatancy; this is probably the reason that pronounced dilatancy is attained with the Hughes material.

Although dilatancy is encountered occasionally when fluid-particle suspensions are being mixed, very little research on it has been reported in the literature. Dilatancy is avoided by paint companies because it causes catastrophic galling of a three-roll paint mill. Plastic fabricators find in mixing fillers into plastic molding compounds that dilatancy can totally wreck high pressure mixing machinery like a Banbury mixer. Consequently, most work reported concerns ways of minimizing the effect.

2. FLUID ARMOR CHARACTERISTICS

Preliminary tests and accumulated experience with the original Fluid Armor composition indicated that its properties were sensitive to changes in fluid or water content. The Fluid Armor compositions are balanced to attain low resistance to low stress levels and high resistance to high stress levels. In this respect, they flow in response to slow motions or under gravity, but rigidize when impacted.

It appears that the best dilatancy is obtained at fluid-solid ratios that are just slightly greater than those required to fill the interparticle

void space or the pores of a packed powder. To establish a range for dilatant behavior, a series of impact tests was made on selected dilatant compositions, using a high-pressure gun.

The test fixture consisted of a 0.187-inch smooth bore tube which received a 0.177-inch diameter air gun pellet. Velocity (and momentum) of the pellet was controlled by means of controlled pressure from an accumulator tank, associated solenoid valve, and pressure regulator. The velocity was measured by determining the time lag between breaking the conductive path of two axially-mounted serpentine targets spaced 1 foot apart, the time interval being measured by an electronic decade counter. Momentum was taken as the independent variable – the product of the weight and the velocity of the pellet. The pellet then struck a 1 × 1-inch cross section cell of dilatant material having a certain controlled thickness. This method duplicated many features of the tests using the armor piercing shell impacts with the added advantage of requiring only a very small sample. It proved quite useful as a screening technique for optimization and for investigation of the variables in Fluid Armor composition. Data were reported as momentum values required to break through the cell 50 percent of the time.

In regard to the critical effect of water content, Figure 1 shows a peak in impact resistance at about 13.5 weight percent water. This curve shows the importance of maintaining good control of composition. Since this behavior has not been previously reported in the literature, more careful work should be done in a future program to characterize fully this critical area to see if this is a true feature of dilatant systems.

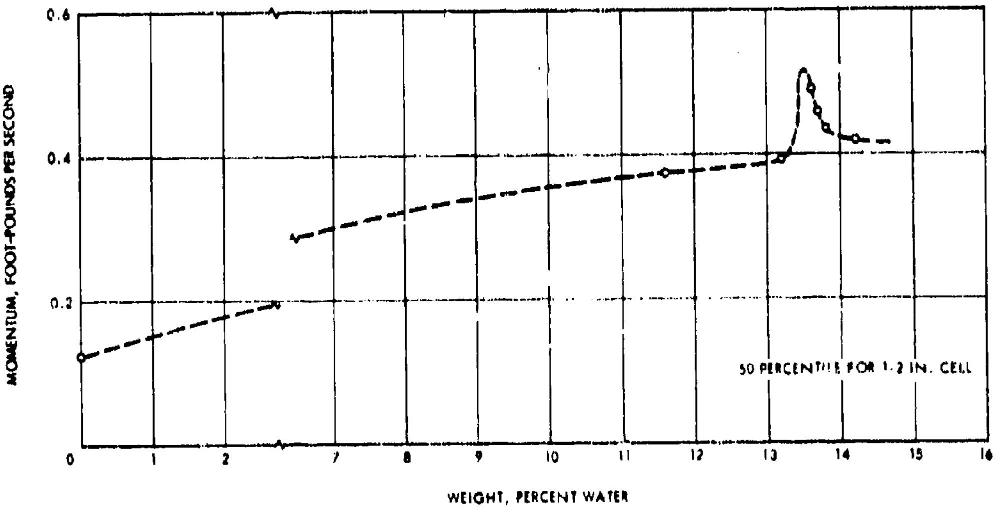

Figure 1. Effect of Water Content on Impact Resistance of Silica-Water System

Figure 2 shows the exponential behavior of the stress-strain properties of dilatant mixtures and also compares the original Fluid Armor to a rather unique titania-water system. The curve includes the correction required for the cell facing material – approximately 0.1 foot-pound per second. The water content of this system is even more critical, but warrants further investigation. Other titanium dioxides which have been studied in a cursory fashion do not display dilatancy to this extent. Systems that may also show promise as alternative materials for future work include certain types of whiting (calcium carbonate) and feldspar. To demonstrate further the wide range of impact resistance typically obtained, values for 50 percent penetration in several compositions are given in Table I in Appendix B.

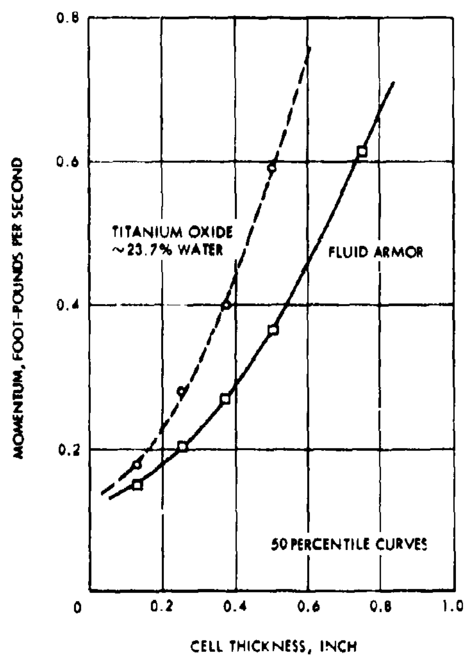

Figure 2. Effect of Cell Thickness on Impact Resistance

3. FIRING TEST SETUP

A 30-06 Springfield rifle was used for all firing tests on Fluid Armor specimens. The rifle was bench-mounted in a sandbagged wooden frame. It was boresighted on target at each daily setup. Each armor test specimen was backed up with twelve 6-inch square by 1/4-inch standard polyester-fiberglass panels. As explained in the next section, effectiveness of an armor specimen was denoted by the number of backup panels penetrated by the AP core after it passed through the

specimen. The specimen and backup panels were bolted between 1 foot square by 3/4-inch thick plywood panels with a 3/8-inch diameter threaded rod. The front plywood panel contained a 4-inch diameter hole in the center to permit unimpeded entry of the bullet into the specimen. A typical assembly is shown in Figure 3. This assembly was sandwiched between two 10-inch inside diameter by 16-inch outside diameter pipe flanges and securely C-clamped or bolted together with 1-inch diameter bolts. Three-foot lengths of 10-inch pipe screwed into the pipe flanges acted as front and back face spallation shields. A large U-shaped shield was inverted over the entire assembly whenever a specimen was tested that was expected to eject fragments laterally. A typical test setup is shown in Figure 4.

Test shots were fired with ball and AP ammunition to determine bullet velocity, target centering, and rifle mount stability. Velocity was measured with a Hewlett Packard Model 523B decade counter connected to a low-voltage trigger circuit and paper breakthrough targets with conductive silver serpentine pattern. Bullet velocity of 2825 ±50 fps was judged sufficiently consistent that velocity measurements were not determined with subsequent tests of armor specimens. Variation between armor samples was much greater than normal variation between bullet velocities.

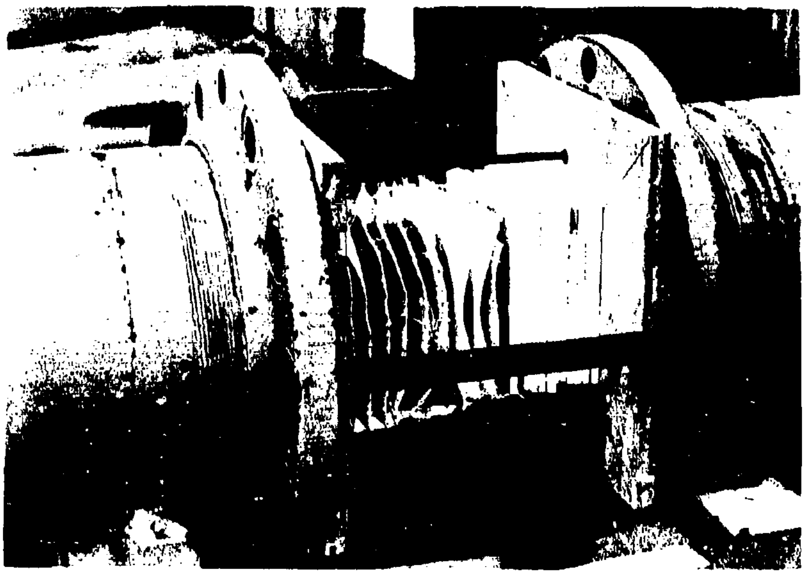

Figure 3. Armor Test Specimen Assembly
(HAC Photo 5R05800)

Figure 4. Firing Test Setup
(HAC Photo 5R05799)

To set standards and to make an initial evaluation of Fluid Armor, a series of shots was conducted on backup panels. Each of the samples in this series consisted of 12 panels of different materials, either spaced 1/4 inch apart or taped or clamped tightly together. Materials were (1) standard 1/4-inch thick No. 1157[1] fiberglass-polyester panels used in conventional ceramic faced armor, (2) similar panels using No. 229 fabric, and (3) 1/4-inch thick high molecular weight polyethylene. All samples with the 1/4-inch spacing between panels failed to stop AP bullets. Caliber 30 ball bullets were stopped by both types of spaced fiberglass panels in five layers. With no spacing between the No. 1157 fiberglass-polyester panels, an AP bullet core was stopped in the tenth panel. High molecular weight polyethylene panels clamped tightly together failed to stop either ball or AP bullets.

In the next tests, 20 layers of two types of ballistic nylon fabric were clamped together and fired upon with ball and AP bullets. Neither fabric stopped either type of bullet. Another identical 20-layer sample of one of the fabrics was prepared with a 1/8-inch thick alumina ceramic facing. It also failed to stop either type of bullet.

A sample consisting of 12 panels of No. 229 fiberglass-polyester panels spaced 1/4 inch apart was prepared with each of the spaces filled with Fluid Armor in polyethylene bags. Another sample was prepared with 11 consecutive layers, each layer consisting of a thin

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[1] For list of suppliers of all materials used in this program, see Appendix A.

polypropylene panel, a ballistic nylon fabric panel, 1/4 inch of Fluid Armor in polyethylene, and No. 229 fiberglass-polyester panel. AP bullets passed through both samples completely, but the ball bullet was stopped in the fifth panel of the first sample and in the fourth layer of the second sample, indicating inconclusively only slight effectiveness of the Fluid Armor packaged in this manner.

At this point, the somewhat discouraging results indicated the need for a better method of ascertaining the degree of armoring effectiveness of any sample or configuration tested. Complexity, expense and uncertainty of results ruled out the use of a ballistic pendulum. But penetration depth into tightly clamped fiberglass panels seemed to be fairly consistent, so this technique was adopted for sample performance comparison in subsequent tests.

To determine if Transite would make an effective substitute for No. 1157 or No. 229 fiberglass-polyester panels as cheaper backup panels, penetration tests were conducted with this material. One Transite sample consisted of 23 layers of 1/4-inch thick panels, a second sample was 12 layers of 1/2-inch thick panels, and a third was five layers of 1-inch thick panels. AP bullets penetrated the first sample completely (but just fell out of the back side of this sample), penetrated the second sample to the tenth panel (5 inches) and broke the eleventh and twelfth panels, and penetrated the third sample into the fourth panel (3-7/8 inches total) and broke the fifth panel. Thus, it is seen that either 1/2-inch or 1-inch thick Transite would serve as fairly good substitutes for fiberglass panels.

To determine penetration of standard Fluid Armor by a 30-caliber AP bullet, a 4-inch inside diameter by 22-inch long steel pipe was fitted with No. 1157 fiberglass-polyester end panels. The pipe was tightly clamped and filled with about 1 gallon of Fluid Armor. A 30-caliber AP bullet was fired into the center of the pipe. Then the end panels were loosened and the Fluid Armor was permitted to leak out slowly so that the bullet parts would be retained at their ultimate penetration distances. The bullet jacket, split in several strips and turned inside out, was found in the pipe 4 inches from the entrance point. The steel core penetrated 12-1/2 inches of the Fluid Armor from the entrance point. The core was smoothly polished by the Fluid Armor particles and had tumbled end-for-end. The penetration shock caused the fiberglass panel at the entrance end to bulge outward about 1/2 inch. This test shows that Fluid Armor will exert enough resistance to stop an AP core if it is laterally confined.

To determine penetration of powdered silica by a 30-caliber AP bullet, a 4-inch inside diameter by 22-inch long steel pipe was fitted with No. 1157 polyester-fiberglass end panels. Silica was vibratory compacted into the pipe. The jacket and core of a bullet fired into the pipe stayed together reasonably well and penetrated 15-1/2 inches of the silica. This test indicated that Fluid Armor showed better effectiveness than dry powder but that the key to its successful use would be found in packaging.

5. EVALUATION OF PACKAGING CONCEPTS

A test program was established in which all packaging concepts as developed were arbitrarily classified in one of the following categories:

- Flexible. Composite containing Fluid Armor is fully flexible and conformable to an irregular surface.
- Semi-Flexible. Composite containing Fluid Armor is flexible enough to shape it around large radii; e.g., 6 inches on irregular surfaces.
- Conformable Rigid. Panels and cellular core making up composite may be formed on mold to irregular shape as with thermoplastics, then filled with Fluid Armor and sealed to make a rigid armor.
- Rigid. Composite is inflexible and non-conformable.

A compilation of test shots is given in Table II in Appendix B. For sources of all structural materials used, see Appendix A.

a. Flexible Composites

(1) Rubberized and Nylon Fabrics

A series of tests was conducted with ballistic nylon and rubberized aviation fuel tank fabrics as encasements for Fluid Armor. Six-inch squares of each material were sandwiched between 4-inch inside diameter steel rings of 1/2-inch thickness made from 4-inch steel pipe to form 12 consecutive cells for the Fluid Armor. This assembly was mounted between 3/4-inch plywood panels and backed up with twelve 6-inch square polyester-fiberglass panels. The entire assembly was bolted tightly between 10-inch inside diameter by 16-inch outside diameter pipe flanges.

Results were varied for the Goodyear rubberized fabrics. The thinnest material, No. A330, (0.015 inch thick, 0.088 pound per square foot) began to strip the jacket off the core in the eleventh and twelfth cells, but pieces were found in the third and fourth backup panels. The core penetrated the sixth backup panel. Performance was better for the H3559A fabric (0.065 inch thick, 0.343 pound per square foot) with jacket fragments and core found in the third backup panel. With the H325A fabric (0.070 inch thick, 0.378 pound per square foot), the jacket was stripped off the eleventh cell, and the core penetrated the first backup panel and had been tumbled 180 degrees. With the A387 material (0.030 inch thick, 0.167 pound per square foot), the jacket was stripped off in the fourth through eleventh cells and the core penetrated the second panel, but was found bounced back into the eleventh cell. From these tests, then, it can be concluded that the H325A

fabric offers the best stopping power in this configuration. But on a weight basis, at less than half the weight per square foot, the A387 fabric is best. To reconfirm results with the A387 material, the test was repeated. Jacket fragments were found in the ninth through twelfth cells, and the core penetrated the second panel, thus showing consistent results.

Tests with Davis Aircraft Products ballistic nylon fabrics showed equivalent performance to the best of the rubberized fabrics. Two tests were conducted with each of two fabrics. With the first test of the A255 fabric (0.085 inch thick, 0.291 pound per square foot), jacket fragments were found in tenth through twelfth cells and into the first panel. The core had tumbled but had nearly penetrated the first panel. In the second test with this material, the Fluid Armor was encased in thin polyethylene bags placed in each cell. Jacket fragments and core penetrated the second backup panel. This indicated that the polyethylene film probably interfered with good coupling normally achieved by Fluid Armor, since the fluid exactly follows irregular contours of ballistic nylon fabric. Results were a little better with the ballistic "M" fabric (0.110 inch thick, 0.325 pound per square foot). No jacket fragments were found in backup panels in either test. The core was tumbled in both tests, and the core was found imbedded in the steel ring in the twelfth cell in one case and had only penetrated the first panel in the second case.

Tests were not conducted with Unicor three-dimensional fluted cloth because the inherent strength of the material was less than that of other fabrics tested.

(2) Fiber Additions to Fluid Armor

Since Fluid Armor has practically no tensile strength and very little shear strength, addition of ceramic, mineral and metal fibers to produce these properties was evaluated. Incorporation of 2 percent chopped Kaowool, the maximum amount that could be mixed easily, greatly increased dilatancy of the Fluid Armor, as shown by penetration resistance to lead shot fired by an air gun. A sample of Fluid Armor sent to the Johns Manville Research and Engineering Center was mixed with a small quantity of asbestos fibers.

As in preceding similar tests, twelve 4-inch inside diameter steel rings of 1/2-inch length were sandwiched between ballistic "M" nylon fabric panels to form assemblies of 12 cells. All cells in each assembly were filled with Fluid Armor samples containing one of the two types of fibers. A 30-caliber AP bullet was fired into each assembly. With the Kaowool fiber additive sample, the AP core penetrated the first backup panel, thereby showing no improvement over the standard Fluid Armor mix. With the asbestos additive sample, the AP core penetrated the third backup panel, showing inferior performance. With both samples, additional water was required to facilitate mixing. The resulting decrease in mixture density may be the reason that

performance was not improved by fiber additions, but this was not pursued further.

Two tests were conducted to determine performance of Fluid Armor filled with coarse steel wool and aluminum wool. In each test, assemblies of 12 cells were prepared as above. Round pads of metal wool were cut to fit the rings, placed inside and the rings filled with Fluid Armor. The assembly was backed up with the usual twelve 6-inch polyester-fiberglass panels.

A 30-caliber AP bullet was fired into each of the assemblies. In the aluminum wool sample, the jacket began to strip off in the fifth cell and was completely removed in the ninth and eleventh cells. The steel core was found lying flat against the first backup panel, but did not penetrate it. In the steel wool sample, the major portion of the jacket was stripped off in the fourth, fifth, and sixth cells, but one large piece was found in the twelfth cell. The core was tumbled in the eighth cell, traveled broadside through the tenth and eleventh cells, and was found in the twelfth cell, having slightly penetrated the first backup panel. Thus, it is seen that, in both cases, the metal wool helped in bullet energy absorption and distribution.

Tests similar to those above were conducted using Scottfoam, a reticulated urethane plastic foam made by Scott Paper Co. No improvement in penetration resistance was detected over the performance of unfilled Fluid Armor. In fact, there was slight evidence that performance was not as good.

(3) Comparison Between AP and Ball Ammunition Penetration

Using the 12 standard 4-inch inside diameter by 1/2-inch length steel confining rings and ballistic "M" nylon layers to form 12 Fluid Armor cells, two tests with 30-caliber ball ammunition were made to compare it with AP ammunition. Penetration was somewhat less consistent; the ball projectile penetrated one backup panel in one assembly and three panels in the second assembly. It is concluded from these tests that Fluid Armor is not effective in breaking up copper-jacketed lead cores any better than AP cores.

(4) Coupling Characteristics of Fluid Armor

A series of tests was devised to evaluate Fluid Armor as a coupling agent between ballistic nylon panels. Steel rings were not used. Instead, 6-inch square 1/8-inch corrugated pasteboard panels containing 3 1/2-inch diameter holes were preapred as separators to form weak-walled cells between ballistic nylon panels. In one test, twelve 1/4-inch Fluid Armor cells were made by putting two separators between each nylon layer. In another test, 12 cells, each 1/8-inch thick, were made by using one separator. Assemblies were backed up with polyester-fiberglass panels and bolted between pipe flanges.

In firing tests, the AP core penetrated the first backup panel after passing through the 1/4-inch thick cell assembly, bounced back out through the side of the pasteboard assembly and deeply dented a steel safety shield. In another test with an identical assembly, the AP core penetrated the second back-up panel, emerged from between the laminations and struck the safety shield. In a third test with an identical assembly, but with 30-caliber ball ammunition, the intact bullet penetrated the third backup panel. In a fourth test, again using ball ammunition, the lead core and some jacket pieces penetrated only the first backup panel.

With the 1/8-inch thick cell assembly, the AP core came to rest in the fourth backup panel. When an identical assembly was tested with 30-caliber ball ammunition, the bullet penetrated the third backup panel with the jacket intact.

To evaluate performance of dry silica powder alone, an assembly was made up using the twelve 4-inch inside diameter by 1/2-inch length steel rings. Silica powder was packed tightly into each cell. In a firing test the AP core bounced off the first backup panel and nearly penetrated the steel confining ring, thus indicating that the powder alone was not as effective in resisting penetration as Fluid Armor.

From these tests, it was concluded that Fluid Armor does provide coupling between ballistic nylon layers, and that stopping power of the composite is improved by thicker Fluid Armor cells.

b. Semi-Flexible Composites

(1) Honeycomb Composites

Two shots were conducted in which 4-inch inside diameter cells containing Hexcel types ALF-40-.0013-1.05 and ALF-40-.003-2.1 Flexcore aluminum honeycomb, separated by ballistic nylon fabric, were filled with Fluid Armor. The first test sample consisted of 11 cells, each 1/2-inch thick. The second sample consisted of six cells, each 1-inch thick. Neither of the two core materials was effective in confining Fluid Armor, allowing penetration of the first backup panel by the AP core in both cases.

(2) Wire Cloth Reinforcement

The standard 12-cell ring assembly was used to evaluate performance of Fluid Armor containing stainless steel wire cloth as reinforcement. Each cell was filled with Fluid Armor and six discs of wire cloth, for a total of 72 wire cloth layers in the 12 cells. Discs of 100 mesh, 40 mesh, and 20 mesh wire cloth were incorporated, respectively, in three assemblies. In firing tests the AP core penetrated the first backup panel after passing through the assembly containing the 100 mesh discs, and the second backup panel after passing through the two assemblies containing the 40 and 20 mesh discs. These tests show

that there is no advantage gained from using wire cloth reinforcement in this manner.

c. Conformable Rigid Composites

A series of tests was conducted on three different types of cellular materials that can be assembled to a particular curved geometry, but are completely rigid after assembly. Panels of various configurations of Halecore, with different facings and screen wire reinforcements as prepared by Halecore, Inc., were filled with Fluid Armor and tested. In the three tests, the material did not offer a great deal of lateral confinement. The bullet core penetrated six backup panels after passing through eight layers (5.2 inches) of the unreinforced No. X1008-21 Halecore panels. The bullet penetrated one backup panel after passing through six layers (3.9 inches) of reinforced No. X1008-22 Halecore panels. In the third test, the bullet penetrated one backup panel after passing through six layers (5.01 inches) of unreinforced No. X1012-21 Halecore panels. Thus it is seen that reinforcing of Halecore improves performance, but that this packaging concept offers no advantage over the fully flexible concepts evaluated and reported on above. Because of these results, no further tests of Halecore and other similar materials were conducted.

d. Rigid Composites

(1) Honeycomb Composites

Tests were conducted with two thicknesses of Hexcel fiberglass honeycomb core materials. Two sets of three 6-inch square panels were prepared, each with 1/2-inch thick Hexcel honeycomb No. HRP 3/4-GF14-1.9 sandwiched between and elastomerically bonded to No. 1157 fiberglass-polyester panels with Proseal 890. Two additional sets of three panels were prepared using 1-inch thick fiberglass honeycomb of identical construction. One set of each of the two thicknesses of honeycomb was filled with Fluid Armor and sealed. The other two sets were left unfilled. All four samples were backed up with standard fiberglass panels as a means of measuring residual energy after sample penetration. AP cores penetrated 11 backup panels after passing through both of the unfilled Hexcel composite samples, and penetrated nine backup panels in both of the honeycomb samples containing Fluid Armor. When the latter panels were opened to analyze penetration effects, it was very obvious that this Hexcel honeycomb provided practically no lateral confinement of the fluid — hence, resistance to penetration of the projectiles was only slight. A very high strength core material is required. No further tests with this type of Hexcel core were conducted.

Twelve alumina ceramic honeycomb panels 3/8-inch thick were filled with Fluid Armor and sandwiched between layers of ballistic "M" nylon. Another similar assembly was prepared with 12 cordierite ceramic honeycomb panels, also 3/8-inch thick. Steel confining rings were not used, but both stacks were placed in thin sheet metal cans for

containment, backed up with 12 polyester fiberglass panels and bolted between 16-inch diameter pipe flanges. In firing tests, the AP core penetrated the third backup panel after passing through the alumina honeycomb assembly and the fifth backup panel after passing through the cordierite honeycomb assembly.

(2) Ceramic Facings

A test was conducted in which nine layers of Coors AD-99 alumina plate (thickness 0.105-inch each) were interleaved between 10 layers of ballistic "M" nylon, each fabric layer heavily coated with Fluid Armor. The purpose of this test was to see if Fluid Armor and ballistic nylon would provide sufficient support to the alumina to cause it to break up the AP core. A firing test revealed that 1/8-inch of the steel core was eroded away, but the core still penetrated three backup panels. Hence, the Fluid Armor and ballistic nylon apparently act as a semi-flexible cushion and do not give adequate support to the alumina.

(3) Filament Wound Structures

Several open ended 12-inch square boxes were filament wound of polyester-fiberglass on an En-Tec Model 24 filament winding machine. The object was to produce backup panels and encasements for Fluid Armor. Since they were far more costly to make than Doron and No. 1157 fabric panels, further work with them was not deemed justified.

SECTION IV

CONCLUSIONS

In this program, Fluid Armor was shown to be capable of stopping 30-caliber ball and AP bullets if properly packaged. However, Fluid Armor was not found to be competitive with ceramic faced rigid armor from the standpoints of weight and volume with all of the packaging schemes evaluated.

Conventional fiberglass and aluminum honeycomb cell strengths were found to be far too low to be effective in constraining lateral motion of Fluid Armor upon impact. Screen wire reinforcements were not effective because of low wire strength and wire slippage. Perforated metal may be effective, but this was not evaluated. None of the Halecore cellular composites was effective for lateral confinement. Fluid Armor packaged in ceramic honeycomb materials showed no improvement over unconfined Fluid Armor. Also, when unconfined, Fluid Armor did not offer satisfactory support for hard ceramic facing materials to permit them to break up hardened steel AP cores. A possible explanation for its effectiveness in shredding lead bullets into fragments is that its apparent instantaneous hardness is greater than that of lead.

Only when Fluid Armor was strongly constrained by steel rings did it show promise in resisting bullet penetration. This observation suggests that, if an exceptionally high cell strength honeycomb material were specially designed and constructed to prevent lateral expansion, it would make an effective package for Fluid Armor. If the new core were flexible, a conformable armor would be possible through use of shingled ceramic platelets as hard facing.

Another important finding of this program was that powdered silica with or without a liquid vehicle improves coupling between layers of flexible high strength fabric, thereby increasing its resistance to penetration by fragments. Use of liquid to make a highly dilatant mixture improves penetration resistance. It would also permit making use of the outstanding self-healing capability of the material.

In view of the unusual performance of Fluid Armor as demonstrated in this program it is recommended that a theoretical study of dilatant materials be undertaken to determine if this dilatant fluid system as well as others might possess characteristics of interest for new applications. For example, certain compositions may be attractive for shipboard or ground based building armor where weight is not a significant factor and other compositions may replace conventional vibration damping fluids, the higher density and non-Newtonian flow behavior being important advantages of a dilatant fluid.

APPENDIX A

MATERIALS AND SOURCES

No. 1157 woven glass roving No. 229 fabric	J. P. Stevens & Co., Inc., Greenville, S. C.
Paraplex P-43 polyester resin (catalyst — Luperco ATC)	Rohm and Haas, Philadelphia, Pa. Lucidol Div., Wallace and Tiernan, Inc., Buffalo, N. Y.
Hi-Fax type 1900 HMW polyethylene	Hercules Powder Co., Wilmington, Del.
AD-99 ceramic facing	Coors Porcelain Co., Golden, Colo.
Ballistic nylon fabric, types "M" and A255	Davis Aircraft Products Co., Northport, Long Island, N. Y.
Transite	Johns-Manville, 611 S. Catalina, Los Angeles, Calif.
Rubberized fabrics, Nos. A330, H3559A, H325A, and A387	Goodyear Aerospace Products, 9800 Sepulveda Blvd., Los Angeles, Calif.
Unicor three-dimensional fluted cloth	Unicor, Inc., Paramount, Calif.
Kaowool	Babcock & Wilcox Co., 1545 Wilshire Blvd., Los Angeles, Calif.
Sil-Temp	Haveg Industries, Inc., Wilmington, Del.
Scottfoam	Scott Paper Co., Foam Division, Chester, Pa.
Flexcore Nos. ALF-40-.0013- 1.05 and ALF-40-.003-2.1 Hexcel No. HRP 3/4-GF14-1.9	Hexcel Products, Inc., Berkeley, Calif.
Halecore Nos. X1008-21, X1008-22, and X1012-21	Halecore, Inc., Gardena, Calif.
Proseal 890	Coast Proseal and Manufacturing Co., Los Angeles, Calif.
Alumina and cordierite ceramic honeycomb	Americal Lava Corp., Chattanooga, Tenn.

APPENDIX B

TABLES

Table I. Comparison of Impact Resistance for Compositions in 1/2-Inch Cells

Base Material	Composition, percent			Impact Resistance, foot-pounds per second
	Base	Water	Glycerine	
Silica (Standard Fluid Armor)	80.8	5.3	13.9	0.458
Silica	86.2	13.8	--	0.436
Silica	100.0	--	--	0.124
Water	--	100.0	--	0.079
Silica –				
with 2 percent Kaowool	80.2	5.2	13.6	0.376
with 2 percent Calcined Kaowool	80.2	5.2	13.6	0.548
with 2 percent Siltemp	80.2	5.2	13.6	0.548
Colloidal Titania	70.3	16.3	13.4	0.497
Colliodal Titania	76.4	23.6	--	0.590
325 Mesh Titania	84.9	15.1	--	0.293

Table II. Data on Selected 30-Caliber Firing Tests

Test Number	Type of Ammunition	Material Tested	Number of Backup Panels Penetrated	Calculated Areal Density without Backup Panels
29	AP	1/2-inch thick Hexcel, unfilled	12	--
30	AP	1-inch thick Hexcel, unfilled	11	--
31	AP	1/2-inch thick Hexcel, filled	9	--
32	AP	1-inch thick Hexcel, filled	9	--
33	AP	Fluid Armor penetration	(12 1/2 inch – no backup panels)	--
34	AP	Silica powder penetration	(14 1/2 inch – no backup panels)	--
36	AP	Goodyear A387 fabric	2	59.6
38	AP	Goodyear H325A fabric	1	62.3
39	AP	Goodyear A330 fabric	6+	58.4
40	AP	Goodyear H3559A fabric	3	62.9
41	AP	Ballistic "M" nylon fabric	0	62.6
42	AP	A255 nylon, Fluid Armor in polyethylene	2	--
43	AP	Ballistic "M" nylon fabric	1	62.6
44	AP	A255 nylon fabric	1	61.2
45	AP	Goodyear A387 fabric	2	59.6
46	AP	Aluminum wool filler	1	--
47	AP	Halecore X1008-21	6	48.3
48	AP	Halecore X1008-22	2	47.6
49	AP	Halecore X1012-21	2	57.8
49A	AP	Scottfoam filler	1	--
50	AP	Steel wool filler	1	--
53	AP	1/2-inch thick Flexcore	1	--
54	AP	1-inch thick Flexcore	2	--
55	AP	Asbestos filler	2	--
56	AP	Alumina ceramic honeycomb	3	--
57	AP	Cordierite ceramic honeycomb	5	--
58	AP	Kaowool filler	1	--
59	AP	Fluid Armor coupling test, 12 1/4-inch cells	1	33.0
60	AP	Fluid Armor coupling test, 12 1/8-inch cells	4	18.6
61	AP	Silica powder	1	41.0
62	Ball	Fluid Armor coupling test, 12 1/8-inch cells	4	18.6
63	Ball	Fluid Armor coupling test, 12 1/8-inch cells	3	18.6
64	AP	Fluid Armor coupling test, 12 1/4-inch cells	2	33.0
65	Ball	Fluid Armor coupling test, 12 1/4-inch cells	3	33.0
66	Ball	Fluid Armor coupling test, 12 1/4-inch cells	1	33.0
67	Ball	Ballistic "M" nylon fabric	3	33.0
68	Ball	Ballistic "M" nylon fabric	1	33.0
69	AP	100-mesh steel screen	1	--
70	AP	40-mesh steel screen	2	--
71	AP	20-mesh steel screen	2	--
72	AP	Alumina ceramic-nylon-Fluid Armor composite	3	--

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13. ABSTRACT
Results are presented on a 9-month evaluation program on resistance to penetration of a highly dilatant fluid by 30-caliber ball and AP bullets. Military ammunition of both types was fired point blank into test cells containing the fluid packaged according to these general concepts: (1) flexible, (2) semi-flexible, (3) conformable rigid, and (4) rigid. The principal objective was to find a fully-flexible system that could use the unusual self-healing capability of the material. Degrees of effectiveness of the various packaging systems for confining the fluid are described in this report. Packaging materials that were tested included commercial fiberglass, high tensile strength plastic, and aluminum honeycomb materials. Cell reinforcements studied included reticulated foam and various grades of screen wire mesh. In an effort to improve shear and short-range tensile strengths of the dilatant fluid, asbestos, metal, and ceramic fiber additives were evaluated. From these tests, Hughes concluded that the dilatant fluid is not competitive with conventional ceramic faced armor on weight or volume bases. But there are indications that the material would be effective if it were tightly constrained in a specially designed high-strength core material. The fluid is shown to improve coupling between layers of flexible high strength fabrics used for protection of personnel against ballistic fragments.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Armor						
Dilatant fluid						
Rheology						
Self repairing armor						
Flexible armor						
Composite armor						